

GAMMA RADIATION FROM RADIO PULSARS

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ABSTRACT

The probable magnetospheric location and source of the γ -ray emission from some young radiopulsars is discussed. The suggested evolution of this emission as a function of pulsar period gives a diminished γ -ray luminosity for a more rapidly spinning pre-Crab pulsar. A greatly enhanced one, similar to that of unidentified Cos B sources, is predicted for a slightly slower post-Vela pulsar, followed by a relatively rapid quenching of the γ -ray luminosity at still longer periods. Possible anomalous exo-magnetospheric pulsed MeV and TeV-PeV radiation from the Crab pulsar is considered briefly.

I. GEOGRAPHY OF THE MAIN GAMMA-RAY EMISSION SOURCE

Among the almost 500 known radiopulsars only the relatively young rapidly spinning Crab and Vela neutron stars are confirmed γ -ray sources. The ultimate sources of this pulsed radiation are particle accelerators powered by neutron star spin-down. There are significant clues in the observed data from these two pulsars which suggest properties and locations of these accelerators.

The pulsed radiation from optical to GeV and perhaps even to 10^{12} eV is coincident to within subpulse peak location measurement accuracy. If the emission source lies within the pulsars' magnetospheres or in the neighborhood of their light cylinder radii (1.5×10^8 cm for the Crab pulsar and 4×10^8 cm for Vela) the emission source position for all of this radiation is probably coincident to within less than 10^4 cm, very much less than magnetosphere radii. Three arguments then suggest that this position, the same for all energetic emission and the non-precursor part of the radio emission, must be very much more than 10 neutron star radii above the stellar surface. Most likely is a source near the light cylinder.

- i) There is evidence (e.g., Dowthwaite *et al.* 1984) that the Crab Pulsar's pulsed γ -ray spectrum extends to at least 10^{12} eV. Such energetic γ -rays could not cross a magnetic field larger than several $\times 10^6$ G without conversion to e^\pm pairs. A magnetic field satisfying the constraint for 10^{12} eV γ -ray to escape is not found within the Crab pulsar's magnetosphere at a radius less than about half the distance to its light cylinder.
- ii) The location of the Crab's optical emission, and, by inference, the X-ray and γ -ray emission coincident with it is constrained by limits on the efficiency of those emission processes which can give optical light. The observed optical intensity (assuming a

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beam shape almost fully extended in latitude as argued below) implies that the optical luminosity efficiency (\hat{f}) satisfies

$$\hat{f} \equiv \frac{L_{\text{opt}}}{L_{\text{KE}}} > \frac{L_{\text{opt}}}{I\Omega\dot{\Omega}} \sim 10^{-5} \quad (1)$$

with L_{opt} the optical luminosity, L_{KE} the rate at which energy is pumped by the spinning star into the kinetic energy of particles which emit the light, and $I\Omega\dot{\Omega}$ the total Crab pulsar spindown power inferred from its measured angular spin frequency (Ω), decay rate ($\dot{\Omega}$) and calculated moment of inertia (I). Acceleration of e^- (or e^+) along \mathbf{B} gives optical radiation with

$$\hat{f}_{\parallel} \ll 10^{-6}. \quad (2)$$

For curvature radiation of photons with energy $\hbar\omega$ from centripetal acceleration

$$\hat{f}_{\text{curv}} \sim \frac{\hbar\omega}{m_e c^2} \frac{e^2}{\hbar c} \sim 10^{-8}. \quad (3)$$

For synchrotron radiation by electrons with Lorentz factor γ and pitch angle θ in a magnetic field \mathbf{B} ,

$$\hbar\omega \sim \frac{\gamma^2 e B}{\sin \theta m_e c} > 10^5 \left(\frac{R_*}{r} \right)^3 \text{ eV}. \quad (4)$$

Here the local Crab pulsar magnetic field is approximated as dipolar and expressed in terms of the ratio of stellar radius (R_*) to radial coordinate r . To achieve the needed strong luminosity at optical frequencies the distance $r \gg 10r_* \sim 10^7 \text{ cm}$. Finally, inverse Compton scattering into the optical regime is hugely suppressed in the presence of the large neutron star magnetic field. Any e^- (e^+) near the star moves along \mathbf{B} (because of very rapid synchrotron loss). In the electron's rest frame the soft photon to be up-scattered to optical energies moves almost parallel to \mathbf{B} . The Thomson cross section for photon scattering (σ_T) to angular frequency ω is then reduced to

$$\sigma \sim \sigma_T \left(\frac{\omega m_e c}{e B \gamma} \right)^2 \sim 10^{-15} \sigma_T \quad (5)$$

near the star. This cross section is much too small for up-scattering of microwave photons to be an important contributor to the Crab pulsar's optical luminosity. Thus only synchrotron radiation from electrons at distances r approaching the light cylinder radius survives among the canonical incoherent processes for optical photon emission from a pulsar magnetosphere.

- iii) The absolute magnitude of the Crab pulsar's energetic radiation luminosity also constrains the emission source location. The maximum net magnetospheric current along (open) magnetic field lines through any pulsar accelerator should not itself give a magnetic field which significantly exceeds the neutron star's own magnetic field anywhere along current flow lines (along \mathbf{B}) between the polar cap ($B \equiv B_*$) and the light

cylinder. This limits the net particle flow through any accelerator which accelerates e^- and e^+ in opposite directions to

$$\dot{N} \lesssim \frac{\Omega^2 B_* R_*^3}{ec} < 10^{34} \text{ s}^{-1}. \quad (6)$$

If the accelerator is near the stellar surface pair production in the 10^{12} G magnetic field (Sturrock 1971) limits the potential drop (ΔV) along \mathbf{B} to

$$\Delta V \lesssim 10^{12} \text{ Volts}. \quad (7)$$

This is much smaller than the $5 \cdot 10^{35} \text{ erg s}^{-1}$ from the Crab pulsar in the X-ray - GeV spectral interval (for a beam shape that gives a similar observed luminosity from almost all directions). Only for $r > 10^7 \text{ cm}$ could local B be low enough to allow ΔV to exceed 10^{14} Volts.

II. EMISSION BEAM STRUCTURE AND EFFICIENCY

We assume (and it is a consequence or assumption of most models) that the electrons and/or positrons injected in the the Crab's dominant magnetospheric particle accelerators are locally produced. For an accelerator close to the stellar surface these pairs could originate in the conversion of 10^2 MeV curvature γ -rays to e^\pm pairs in the huge stellar magnetic field. However, for accelerators as far from the star as indicated above $\gamma + \gamma \rightarrow e^+ + e^-$ is a much more important pair production mechanism. If there is strong e^\pm production and acceleration of e^-/e^+ in the Crab magnetosphere where $r \gg R_*$, the associated radiation from these electrons (or their progeny) has several properties which are not dependent upon the detailed way in which the acceleration and radiation are achieved.

- 1) Because initially accelerated e^-/e^+ move relativistically along local \mathbf{B} most of the primary energetic radiation is emitted parallel to the \mathbf{B} at the accelerator. The flow of $e^-(e^+)$ accelerated toward the star will be approximately matched by $e^+(e^-)$ flowing away from it. The same is true for any e^\pm pairs created by γ -rays from the accelerator in locations where e^\pm are not separated by local electric fields along \mathbf{B} . It follows from this that the emission from around these $e^- - e^+$ symmetric accelerators must consist of four beams of similar strengths (cf. Figure 1). First, a beam from outward (i.e., moving along \mathbf{B} away from the neutron star) moving $e^-(e^+)$ or e^\pm pairs. Second, an almost equivalent beam from inward (i.e., moving along \mathbf{B} toward the star) moving $e^+(e^-)$ or e^\pm pairs. Finally phenomena on open \mathbf{B} -field lines connected to the star at a polar cap should be matched by very similar ones on \mathbf{B} -field lines from the opposite polar cap. Because the radiation source is so far from the stellar surface all of the radiation ultimately escapes through the light cylinder. (For near surface accelerators inward directed beams could be blocked.)
- 2) These four beams (only two of which would be visible to any observer) should have a very large longitudinal spread. This follows because the needed accelerator potential

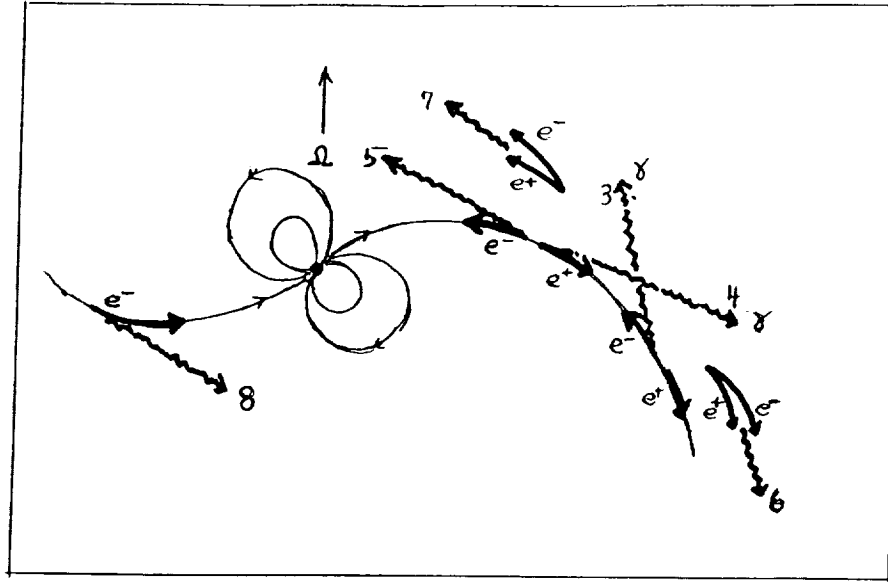


Figure 1. The geometry for photon emission from outer-magnetosphere accelerators which accelerate e^-/e^+ along local \mathbf{B} with an electric field component $\mathbf{E} \cdot \hat{\mathbf{B}}$ within the accelerator. The resulting radiation from curvature radiation, synchrotron radiation, or inverse Compton scattering is a fan covering almost all latitudes. Similar beams go outward (4, 6) and inward (3, 7). Because of dipolar symmetry the observer who sees outward moving photons (4) in one subpulse will also see inward moving photons (8) from the other side of the star in a later arriving second subpulse as the star rotates. Gamma-ray beam crossing such as shown for 3 and 4 will sustain e^\pm production around the accelerator.

drop in the Crab magnetosphere ($\Delta V > 10^{14}$ Volts) and the associated electric field along \mathbf{B} ($\mathbf{E} \cdot \hat{\mathbf{B}} > 10^6$ Volts cm^{-1}) are so large that accelerated e^-/e^+ quickly achieve energies that are radiation reaction limited (by curvature radiation if inverse Compton scattering on abundant soft photons does not limit accelerated e^-/e^+ energies first). As a result the primary radiation, and that from secondary pairs, is determined by the accelerator $\mathbf{E} \cdot \hat{\mathbf{B}}$ which tends to be flat through the accelerator (rather than the potential drop which grows monotonically from one end to the other). The very large ΔV needed in the outer magnetosphere can be achieved only in a very long accelerator. Therefore similar γ -ray emission is expected for great distances along a downward (upward) curving \mathbf{B} -field line through the relevant accelerators. One consequence is a large probability that any observer would see two beams of energetic radiation from the accelerator no matter what the angle between the pulsar's spin (Ω) and its dipole moment or the direction to the observer. This suggested geometry (Figure 1) receives some support from two features of the observed optical, X-ray and γ -ray radiation from several young pulsars. First, searches of the Crab and Vela supernova remnants and also that containing PSR 0540-693 for such young pulsars did indeed discover them. If the rotating beams were cone-like with longitudinal widths comparable to their observed widths in latitude such a success rate would be highly improbable. The

a priori probability for intercepting both the Crab and Vela energetic radiation beams would not have exceeded about 1/25. Longitudinally extended fan-like beams (or very wide angle hollow cones) are more plausible alternatives. Second, all three pulsars have a double beam structure. While the large 140° subpulse separation of the Crab and Vela pulsars might suggest successive observation of North and South magnetic poles, the very much smaller 80° separation observed in PSR 0540 (Middleditch and Pennypacker 1985) argues against such an interpretation. However these separations are quite compatible with the geometry of Figure 1 where aberration and time of flight differences would give observed subpulse phase separations which can vary greatly for different viewing or tilt angles (e.g., photons 4 and 8 of Figure 1 would arrive at any observer with a time separation comparable to the time of flight difference across the light cylinder, i.e., Ω^{-1}).

- 3) Because radiation reaction limits the e^-/e^+ energy achieved in the accelerator essentially the full potential drop energy $e\Delta V$ is radiated away from the accelerator. Thus the magnetosphere accelerator is almost 100 percent efficient as a radiation source.
- 4) Finally, the expected accelerator geometry has crossing γ -ray beams in the outer-magnetosphere (e.g., beams 3 and 4 of Figure 1) which gives copious e^\pm production from $\gamma + \gamma \rightarrow e^- + e^+$ (or $\gamma + X \rightarrow e^- + e^+$ with $10^2 - 10^3$ MeV γ -rays).

III. AN EMISSION MODEL

It has been argued elsewhere (Ruderman 1987a, Cheng, Ho, and Ruderman 1986 a,b, hereafter CHR I and II) that expected current flow in many young pulsar magnetospheres can lead to charge deficient regions ("gaps") in which $\mathbf{E} \cdot \hat{\mathbf{B}}$ grows until limited by pair production processes. For Crab pulsar or PSR 0950 outer-magnetosphere parameters a series of processes can give self-sustained e^\pm production and associated energetic radiation:

- a) Any e^\pm produced in an accelerator gap is instantly separated by large $\mathbf{E} \cdot \hat{\mathbf{B}}$. Because of magnetic field line curvature each oppositely accelerated lepton radiates multi-GeV curvature γ -rays.
- b) These γ -rays collide with KeV X-rays, from d) below, to make e^\pm pairs. Pairs created in the accelerator gap itself repeat process a) above.
- c) In the Crab magnetosphere pairs created beyond the gap boundary lose their energy to optical-MeV synchrotron radiation and also to higher energy γ -ray creation when they inverse Compton scatter on the same X-ray flux which was responsible for their creation.
- d) The X-ray flux from synchrotron radiation is also that which originally caused materialization of the curvature γ -rays of b) and the inverse Compton scattering of c). Because of the beam crossing of Figure 1, e^\pm and γ -rays interact mainly with the crossing X-ray flux radiated by the oppositely directed pairs.
- e) A further generation of e^\pm pairs from crossed γ -ray fluxes of c) radiates soft photons extending down to far IR for Vela (CHRII). Some of this passes through the accelerator gap where it can be inverse Compton scattered by primary gap accelerated e^-/e^+ .

This cyclic chain a) – c) of processes, bootstraps a self-sustained emission of radiation with calculated self-consistent spectra shown in Figures 2 and 3 for Crab and Vela parameters (CHR I and II). Calculated intensity spectra for PSR 0540 are compared with optical and X-ray observations and GRO thresholds in Figure 4 (Ho 1989).

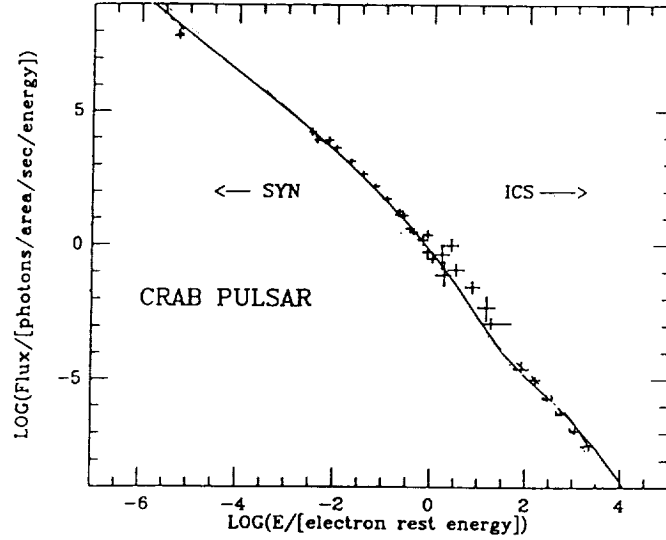


Figure 2. Comparison of Crab pulsar observations and a model prediction for an outer-magnetosphere gap. (The normalization is adjusted arbitrarily.) SYN refers to synchrotron radiation and ICS to inverse Compton (from CHR II).

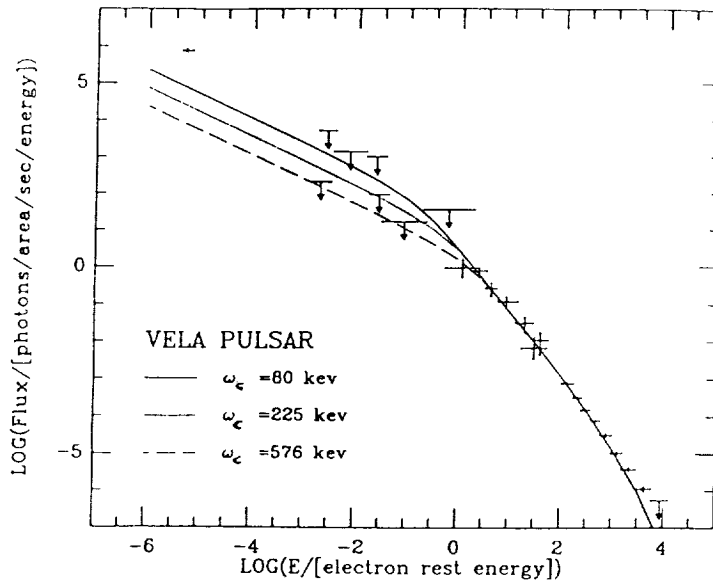


Figure 3. Comparison of Vela pulsar observations and model predictions from CHR II. The ω_c refer to Eq. (8).

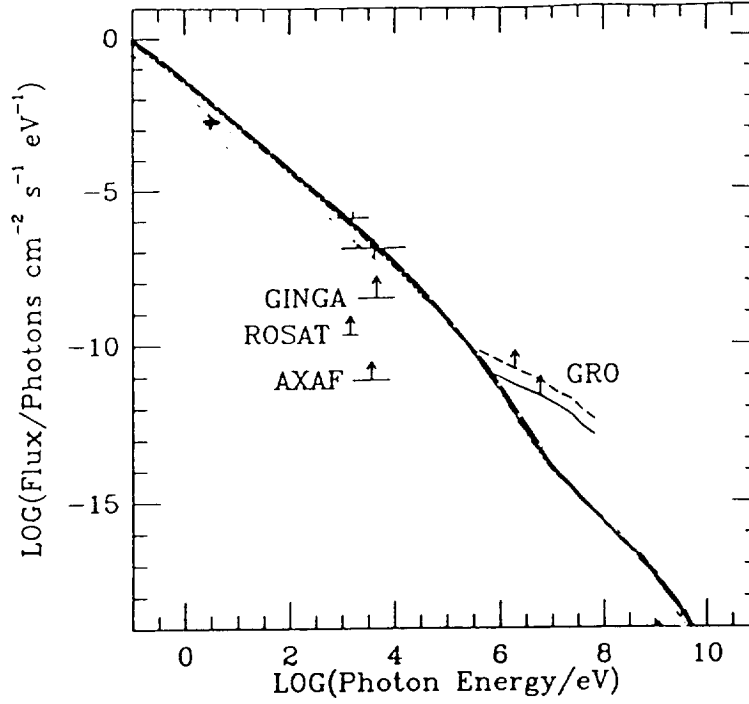


Figure 4. Observations and model predictions for PSR 0950 (Ho, 1989). GRO thresholds are also indicated.

The calculated break in the Vela spectrum which greatly suppresses the X-ray part of the spectrum is a direct consequence of the limited time (τ) spent by synchrotron radiating e^\pm pairs in the outer-magnetosphere. Those pairs moving inward are reflected in the converging \mathbf{B} -field and join with outward moving pairs in passing out through the light cylinder. The critical synchrotron radiation frequency (ω_c) achieved by the e^\pm pairs before this happens has a τ and local B dependence (CHR II)

$$\omega_c \propto \tau^{-2} B^{-3} \propto \tau^2 \Omega^{-9} \propto \Omega^{-7} \quad (8)$$

A spectral break calculated to occur at around 40 eV in the Crab spectrum would be at 10^2 keV in Vela's if additional corrections relating to initial pitch angle are neglected.

The rough agreement of calculated spectra and subpulse features from such outer-magnetosphere accelerator models with those observed (Figures 2, 3, and 4) may support using such models to predict the dependence of γ -ray luminosity on pulsar period (P).

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IV. GAMMA-RAY PULSAR EVOLUTION

Calculated γ -ray luminosities of Crab-Vela type γ -ray pulsars ($B_* \sim 3 \cdot 10^{12} \text{G}$) as a function of a pulsar period is given in Figure 5 (Ruderman and Cheng 1988, Ruderman 1987b). For $P < P_{\text{crab}}$, B in the outer-magnetosphere is greater than that of the Crab pulsar at the same fractional distance of its light cylinder. One consequence is that it is much easier to limit the growth of outer-magnetosphere accelerator gaps by pair production. The γ -ray luminosity, which equals the accelerator power needed to achieve this limit, is roughly proportional to P in this regime. The Vela pulsar has a much different mix of the processes a) – e) of Section II than that in the larger (local) B of the Crab outer-magnetosphere. A much larger fraction (f) of its total spin-down power appears in L_γ ($f \sim 10^{-2}$) than was the case for the Crab ($f \sim 10^{-3}$). As the pulsar period grows beyond Vela's, local B decreases and ω_c increases well above an MeV so that the efficiency for $\gamma + \gamma \rightarrow e^- + e^-$ is diminished: an increasing f and L_γ are then required to sustain needed outer-magnetosphere e^\pm production. L_γ grows until it somewhat exceeds $10^{36} \text{erg s}^{-1}$ and $f \rightarrow 1$. No further growth is then possible and self-sustained outer-magnetosphere accelerator pair production ceases for still longer P . The estimated number (~ 40) and luminosity of such intense γ -ray sources are of the same order as those of the still unidentified strong Cos B sources. It is tempting to propose that these Cos B sources are indeed dying Vela type γ -ray pulsars. Even if various outer-magnetosphere accelerator details do not survive, the general argument that lengthening P beyond Vela's will increase f (a growth already apparent in the transition from the Crab to Vela pulsars) may be expected to be quite robust so that the predicted growth in L_γ and subsequent γ -ray turn-off should remain valid.

Strong γ -ray sources may also be achieved for much smaller P when B_* is small enough. The magnetospheres of many members of the millisecond pulsar family resemble the outer-magnetosphere of the Vela family so that many of them may be detectable as strong γ -ray pulsars.

The crucial question of how canonical radio pulsars may continue to be radio emitters even if strong outer-magnetosphere e^\pm production is quenched has been discussed elsewhere (Ruderman and Cheng 1988, Ruderman 1987b).

V. OTHER ORIGINS FOR CRAB PULSAR MeV AND TeV RADIATION

Because the Crab model calculations and observations cover a spectral interval of 10 orders of magnitude and a photon flux spanning 20 the log-log plot of Figures 2, 3 and 4 show a rather promising fit. The data theory comparison in Figure 6 (Ho 1989) more clearly emphasizes the differences between theory and observations. We note first that the calculated synchrotron light is almost an order of magnitude larger than that observed. However, the Crab model calculation does not exploit the spectral break of Equation 8 which is predicted to be near optical frequencies for the Crab outer-magnetosphere. Its inclusion can very significantly reduce model predictions. The failure of the model to reach observed intensities around an MeV raises more serious questions. The data themselves have been acquired in a variety of different programs and show considerable scatter and lack of consistency. The largest observed excesses over model calculations are generally

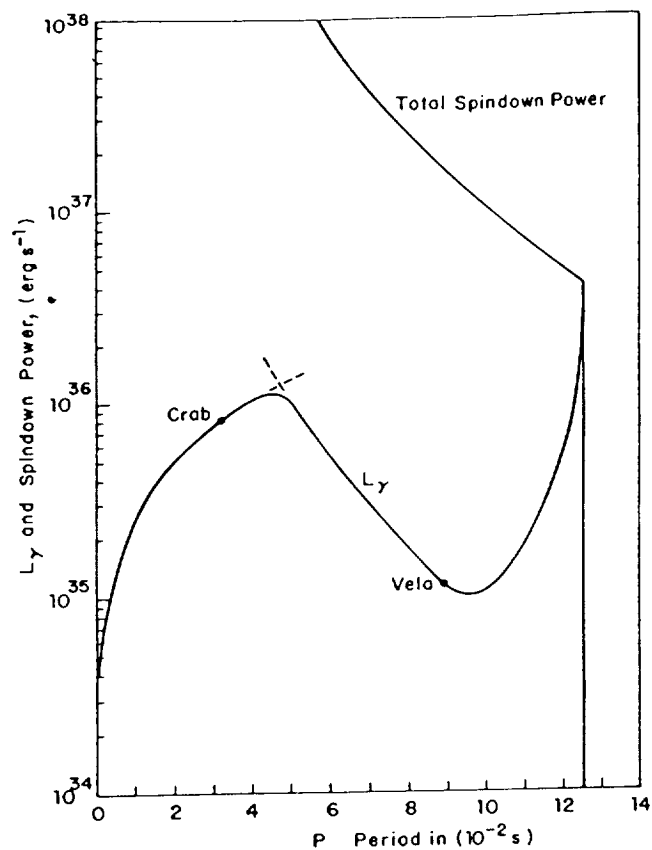


Figure 5. Model calculations for the evolution of the γ -ray luminosity (L_γ) of a strongly magnetized ($B_* \sim 3 \cdot 10^{12} \text{G}$) pulsar as a function of pulsar period (P) (Ruderman and Cheng 1988).

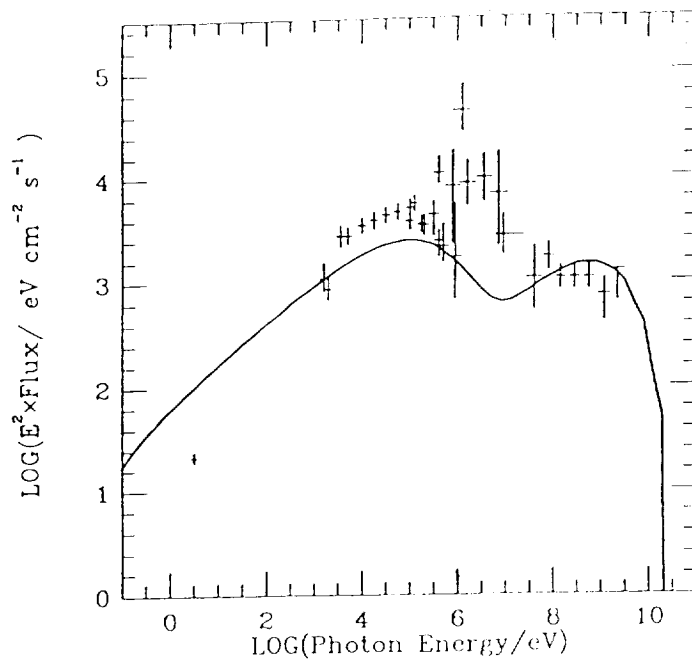


Figure 6. Emitted energy per decade of photon frequency for the crab pulsar (Ito, 1989).

those from long term observations from satellites; rocket, and balloon flight data have been closer to theoretical predictions (cf. Schönfelder 1983, White *et al.* 1985, Graser and Schönfelder 1982). It is, perhaps, possible that much of the excess is in transient activity usually missed in shorter time observations. A spectrally broad (transient) excess around an MeV may possibly have a very different kind of origin from the rest of the Crab pulsar emission. Most of the Crab spin-down power is probably carried beyond the magnetosphere light cylinder as a 30 Hz (electro-)magnetic field spun off by the rotating dipole of the neutron star and a TeV – PeV e^\pm wind. The pairs are created within the magnetosphere (Section IIIe) but receive most of their ultimate energy beyond it from acceleration by the magnetic dipole radiation. This ultra-relativistic e^\pm wind (whose power may approach $5 \cdot 10^{38} \text{ erg s}^{-1}$) can inverse Compton scatter on the pulsar's radio and optical emission. Near the magnetosphere where there is still a significant angle between the wind direction and that of the radiation photons (both approach exact radial flow only far from the magnetosphere). Inverse Compton scattering of the very abundant photons at the low end of the pulsar's radio emission spectrum may convert enough of these into MeV γ -rays to give a dominant contribution to the observed pulsed γ -ray photons in that spectral region. A large additional pulsed inverse Compton contribution by the Crab pulsar's exo-magnetospheric outgoing e^\pm wind would then also be expected from inverse Compton scattering on the abundant pulsed soft X-ray emission coming from within the magnetosphere. These up-scattered γ -rays should acquire up to the full TeV–PeV energy of the wind electrons. Transient pulsed 10^{14} eV γ -rays from the Crab have indeed been reported recently (Rao 1989) in simultaneous observations by the Kolar Gold Field air-shower group in India and the Baksan group in the USSR. Both the high luminosity ($3 \times 10^{36} \text{ erg s}^{-1}$ if isotropic) and γ -ray energy would make a magnetospheric origin for this radiation implausible (10^{14} eV γ -rays cannot traverse $B \gtrsim 10^4 \text{ G}$).

I am happy to thank Drs. V. Schönfelder and C. Ho for very helpful remarks.

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DISCUSSION

Chuck Dermer:

1) In your model for the Crab pulsar, what is the magnetic field strength where the X-rays are comptonized by high energy electrons? Could resonant magnetic compton scattering be important? 2) Are the high energy gamma-rays produced by photopion production from accelerated high-energy protons susceptible to attenuation from gamma-gamma or gamma-B pair production before escaping?

Mal Ruderman:

1) The relevant magnetic field is somewhat dependent upon the geometry of the neutron star dipole moment, spin axis, and observer direction. It is in the $10^6 - 10^7$ G range. The compton scattering electrons still have relativistic momentum components perpendicular to the local B. In such a case I don't think there are any longer large resonant effects. 2) TeV gamma-rays would be strongly absorbed if they pass through the Crab pulsar's optical photon beam unless the passage occurs well beyond the light cylinder (or if the optical beam has holes). PeV gamma-rays must also avoid passage through a magnetic field stronger than 10^4 G which would again put their origin well beyond the light cylinder.

